Ultra-High Energy Cosmic Rays : a Window to Post-Inflationary Reheating Epoch of the Universe ?

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Abstract

We conjecture that the highest energy cosmic rays, $E > E_{GZK}$, where $E_{GZK} \sim 5 \cdot 10^{19}$ eV is the Greisen–Zatsepin–Kuzmin cut-off energy of cosmic ray spectrum, may provide a unique window into the very early epoch of the Universe, namely, that of reheating after inflation, provided these cosmic rays are due to decays of parent superheavy long-living X-particles.

These particles may constitute a considerable fraction of cold dark matter in the Universe. We argue that the unconventionally long lifetime of the superheavy particles, which should be in the range of $10^{10} - 10^{22}$ years, might require novel particle physics mechanisms of their decays, such as instantons. We propose a toy model illustrating the instanton scenario.

Generic expected features of ultra-high energy extensive air showers in our scenario are similar to those of other top-down scenarios. However, some properties of the upper part of the cosmic ray spectrum make the instanton scenario distinguishable, at least in principle, from other ones.

1. Among the top-down mechanisms attempting to explain the observations [1] of ultra-high energy (UHE) cosmic rays beyond the Greisen–Zatsepin–Kuzmin cut-off [2] , decays of primordial heavy particles are most obvious possibility. It is clearly more conventional — at least at first sight — than scenarios invoking topological or non-topological defects [3], though the latter may be a viable alternative. Heavy particles with lifetime of the order of the age of the Universe or greater may constitute (a substantial fraction of) cold dark matter, so the two observed features of the Universe — ultra-high energy cosmic rays and dark matter — may be related to each other.

To get an idea of the range of properties of decaying particles (X-particles) that supposedly produce UHE cosmic rays, let us make the following simple observations.

First, assuming sizeable hadronic component (jets) among the decay products, the flux of protons or gammas of energy E on the Earth is estimated as

$$\frac{dF}{d\ lnE} = \frac{1}{4\pi}\frac{n_X}{\tau_X}R_{p,\gamma}N_j\frac{dN_{p,\gamma}(E)}{d\ lnE}, \tag{1}$$

where N_j is the number of jets in a typical decay, $R_{p,\gamma}$ is the effective distance to X-particles, n_X is the number density of X-particles at the scale $R_{p,\gamma}$, τ_X is the X-particle lifetime and $dN/d\ lnE$ is the fragmentation function. In the following estimates we take $N_j \sim 1-10$ (we will soon see that large jet multiplicity may be favored in some decay scenarios) and $dN_{p,\gamma}/d\ lnE \sim$ (a few) $\cdot\ (10-100)$ in the energy range of interest, $E >$ (a few) $\cdot\ 10^{10}$ GeV (the latter estimate comes from bold extrapolation of the fragmentation functions of ref.[4] to extremely high jet energies). For the effective distance we take $R \lesssim 100$ Mpc, with understanding that the actual value of R may be much smaller than 100 Mpc if X-particles are clumped. In fact, our conclusions will be fairly insensitive to the actual values of the above parameters.

The second relation is

$$m_X < n_X >= \Omega_X\rho_{crit}, \tag{2}$$

where $< n_X >$ is the average number density of X-particles and $\Omega_X \lesssim 1$. If X-particles are clumped, the density n_X entering Eq.(2) may be several orders of magnitude larger than $< n_X >$. Again, this uncertainty will not affect our main conclusions, and we set $n_X \sim\ < n_X >$ in what follows. In order to produce cosmic rays of energies $E \gtrsim$ (a few) $\cdot\ 10^{11}$ GeV, the mass of X-particles is to be very large, $m_X \gtrsim 10^{13}$ GeV.

Let us now estimate the range of X-particle densities required. From Eq.(2) we find a bound for the present X-particle density-to-entropy ratio

$$n_X/s \lesssim 10^{-21}. \tag{3}$$

On the other hand, to produce the observed flux of UHE cosmic rays, the density of X-particles should not be too small. Keeping in mind that their lifetime, τ_X, cannot be much smaller than the age of the Universe,

$$\tau \gtrsim 10^{10}\ yr, \tag{4}$$

we obtain from Eq.(3)

$$n_X/s \gtrsim 10^{-33}. \tag{5}$$

Even though the window for n_X is very wide, the estimates (3) and (5) raise the issue of the production of X-particles in the early Universe.

Alternatively, Eqs.(3) and (5) may be used to place an upper bound on the lifetime of X-particles,

$$\tau_X \lesssim 10^{22} \ yr. \tag{6}$$

Again, the window for τ_X is wide, but the estimates (5) and (6) indicate another problem, namely, that of the particle physics mechanism responsible for long but finite lifetime of very heavy particles.

In the rest of this paper we propose possible scenarios for i) generating the abundance of X-particles in the range (3), (5) by processes in the early Universe, and ii) explaining the lifetime of X-particles in the range (4), (6).

Before coming to our main points, let us stress that these two problems inherent in theories with very heavy and almost stable particles were realized long ago (see, e.g., ref.[5] and references therein) in different contexts. In ref.[5] it was proposed that the problem i) may be solved by large entropy generation in the Universe after the heavy particles freeze out of thermal equilibrium, while their long lifetime may be due to very large dimension of operators responsible for the decay. We leave for the reader to judge how exotic are alternative possibilities that we discuss below.

2. If the temperature in the early Universe at some epoch exceeded the mass of X-particles and then decreased smoothly without large entropy generation, the freeze-out density of X-particles would greatly exceed the bound (3). A way out of this problem is provided by inflation and subsequent reheating. To explain the small abundance of X-particles, the reheating temperature T_r must be much smaller than m_X, so that X-particles were never at thermal equilibrium after inflation. In that case X-particles-to-entropy ratio is exponentially small,

$$n_X/s = \text{const}{\cdot}\exp(-2m_X/T_r), \tag{7}$$

where the constant depends on a number of factors (the coupling constant responsible for pair production of X-particles, the effective number of degrees of freedom, the ratios m_X/T_r and M_{Pl}/m_X, etc.) and is of order 10^{-3} with several orders of magnitude uncertainty. As the dominant suppression comes from the exponential factor, the reheating temperature can be estimated from (3), (5) fairly precisely,

$$T_r = \left(\frac{1}{20} - \frac{1}{35}\right) m_X, \tag{8}$$

and should be in the range $10^{11} - 10^{15}$ GeV, depending on m_X. Note that this range is realistic in many scenarios of inflation.

Hence, inflationary scenario can easily explain small value of the present density of X-particles in the space. Conversely, the determination of m_X from measurements of the upper end of cosmic ray spectrum would allow for rather precise estimate of the reheating temperature. Ultra-high energy cosmic rays may indeed serve as a window to reheating epoch in the early Universe.

3. Explaining long lifetime of X-particles is much harder. Conventional perturbative mechanisms cannot be responsible for cosmologically large τ_X (unless very high dimension operators are involved [5]), so one turns naturally to non-perturbative phenomena. A well known example is instantons that produce exponentially small effects in weakly coupled theories. If instantons are responsible for X-particle decays, the lifetime is roughly estimated as

$$\tau_X \sim m_X^{-1} \cdot \exp(4\pi/\alpha_X), \tag{9}$$

where α_X is the coupling constant of the relevant (spontaneously broken) gauge symmetry. From Eqs.(4), (6) we find that the coupling constant (at the scale m_X) is

$$\alpha_X = \frac{1}{10} - \frac{1}{12}. \tag{10}$$

Hence, we are lead to introduce additional non-Abelian gauge interactions with fairly large coupling constant at high energy scale.

To illustrate this possibility let us consider a toy model with $SU(2)_X$ gauge interactions added to the Standard Model. The $SU(2)_X$ gauge symmetry is assumed to be broken at sufficiently high energy scale. Some conventional quarks and leptons carry non-trivial $SU(2)_X$ quantum numbers (say, $SU(2)_X$ may be right-handed subgroup of a left-right symmetric theory, or it may be a horizontal group with generations forming $SU(2)_X$ triplets). Let there be two[1] left-handed $SU(2)_X$ fermionic doublets X and Y and four right-handed singlets, all of which are singlets under $SU(2)_L \times SU(3)_c$ of the Standard Model. After $SU(2)_X$ breaks down, all X- and Y-particles acquire large masses in a manner similar to the Standard Model. We further assume that X and Y carry different global quantum numbers, so there is no mixing between them.

Under these assumptions the lightest of X-particles and the lightest of Y-particles (we call them X and Y at certain risk of confusing notations) are perturbatively stable. However, $SU(2)_X$ instantons induce effective interactions violating global quantum numbers of X and Y. Say, if X is heavier than Y, then $SU(2)_X$-instantons lead to the decay

$$X \to Y + quarks + leptons \tag{11}$$

with the rate estimate given by Eq.(9). It is this type of processes that may be responsible for the production of ultra-high energy cosmic rays.

Let us point out a few features of this scenario which seem generic.

i) Decays induced by instantons typically lead to multiparticle final states. The number of quarks (jets) produced in the process (11) should be rather large, of order 10, and their distribution in energy should be fairly flat. In principle, the spectrum of cosmic rays within this scenario should be distinguishable from the spectrum predicted by other mechanisms (like two-jet decays of heavy particles born in the interactions of topological defects). Also, there are necessarily hard leptons among the decay products in the process (11).

ii) If Y-particles are indeed perturbatively stable, they are also stable against instanton-induced interactions (because of energy conservation and instanton selection rules). Then the dark matter in the Universe may consist predominantly of Y-particles, while the admixture of X-particles is small. Since the abundance of Y-particles is given by the formula similar to Eq.(7), and since the density of X-particles is bounded from above, Eq.(5), the mass splitting between X- and Y-particles should not be large,

$$m_X < 2m_Y. \tag{12}$$

Alternatively, the Higgs sector and its interactions with fermions may be organized in such a way that Y-particles are in fact perturbatively unstable (while X-particles remain perturbatively stable). In that case the heavy candidates for dark matter are X-particles, and the approximate degeneracy (12) need not hold.

[1]The $SU(2)_X$ anomaly prevents the number of $SU(2)_X$ doublets from being odd.

iii) Because of the instanton selection rules, this scenario for the slow decay of heavy particles is rather restrictive. For example, X-particles cannot be colored (otherwise the $SU(2)_X$ instanton vertex would include at least three X-fields); if Y-particles are stable, they cannot be colored either. This fits nicely to the expectation that dark matter particles do not experience strong interactions. On the other hand, X-particles (and Y-particles, if stable) cannot be weak doublets for the same reason, so the heavy dark matter in this scenario does not have electroweak interactions, too.

To conclude, an explanation of ultra-high energy cosmic ray events beyond the GZK cut-off by decays of hypothetical heavy particles of cosmologically long lifetime is not unrealistic from both cosmological and particle physics points of view. Detailed study of the upper end of cosmic ray spectrum will provide insight into the decay mechanism involved, and allow for the determination of the mass of X-particles. As the latter has been argued to be related to the reheating temperature, the ultra-high energy cosmic rays may become a clue to the end-of-inflation epoch in the early Universe.

After this work was presented at this Conference, we received a paper by Berezinsky, Kachelriess and Vilenkin [6] where the decays of heavy particles have been also considered as the origin of cosmic rays beyond the GZK cut-off. Their main point is that X-particles are expected to concentrate in the galactic halo, and in this way one easily avoids the constraints coming from the analysis of the cascade radiation [7]. Their proposal for long but finite lifetime of X-particles is that it is due to quantum gravity (wormhole) effects.

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